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13. ABSTRACT

The purpose of this research project is to apply the systems approach to the tunnelling process and to the materials handling function in particular. This report covers the literature search, the study of existing methods, and the development of the conceptual model. The literature search revealed a large amount of descriptive information on the equipment and methods used in tunnelling systems. However, applications of research into the rapid excavation field were generally scarce.

Study of present tunnelling methods led to the formulation of a conceptual model of a tunnelling system. The system has been broken down into four unit operations designated as muck generation, tunnel support, environmental control, and materials handling. The modelling of each of these operations is discussed. The interaction between the unit operations will be handled by the simulation control system which also performs the input-output and accounting functions. Emphasis has been placed upon designing the control system to simulate nearly any tunnelling operation.

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SUMMARY

The main purpose of this research project is to apply the systems approach and the technique of computer simulation to the process of tunnelling by rapid excavation methods. Of particular interest is the optimization of the materials handling function for tunnelling systems. The portions of the project reported upon here include the search of the literature, a study of existing tunnelling methods, and the development of the conceptual model of a general tunnelling system which is to be programmed on a computer for purposes of systems analysis.

The review of the literature revealed a large amount of descriptive information on the present tunnelling methods. In particular, the literature contained a good deal of information on the types of equipment used in driving both hard rock and soft-ground tunnels. The design of tunnelling machines, the cutting tools used, and the materials handling methods were of interest in this project. Track haulage was found to predominate for materials handling in tunnels at present but continuous methods are probably more likely to be used as rapid excavation technology advances. Applications of rock mechanics and systems analysis to rapid excavation were generally scarce, pointing out the need for research in this area.

The study of the methods in present use resulted in the formulation of the conceptual model of a general tunnelling

system. For purposes of the model, the tunnelling systems have been broken down into four unit operations which have been designated as muck generation, tunnel support, environmental control, and materials handling. Each of these unit operations is discussed along with the concepts to be used in modelling on the computer. Special attention has been paid to the materials handling subsystem since it is the most complex and offers the greatest possibility of improvement in production from a systems standpoint. The interaction between the various unit operations is a very important part of the simulation approach and will be handled by the simulation control system which will also be programmed to control the input-output and accounting functions. Emphasis has been placed on designing the control system to accommodate nearly any tunnelling system and any set of priorities which may exist among the unit operations. The research for the next reporting period will consist of the programming of the model and testing the model on actual tunnelling systems.

REVIEW OF PERTINENT LITERATURE

The concept of tunnelling by machine is not a very new idea. In 1882, a tunnel 6000 feet in length was driven beneath the English Channel using a boring machine. Although the tunnel was never completed, it illustrates how long the principle of mechanical tunnelling has existed. The recent resurgence of interest in machine tunnelling began in the late 1950's and resulted in the development of numerous successful machines for boring tunnels in both hard and soft ground. In addition, it has resulted in a large number of articles and publications in the engineering literature. Most of these publications are descriptive in nature and do not deal with the scientific or technical aspects of tunnelling. However, the success of the rapid excavation process has encouraged research in this area which will undoubtedly result in more scientific publications in this field in the future.

The review of the literature presented here will cover the areas in the literature which are of interest in computer simulation of rapid excavation systems including the demand for rapid excavation processes, the methods and materials handling systems used in tunnelling, and the rock mechanics and systems analysis applications in the rapid excavation field.

The Demand for Tunnelling Systems

Significant attempts have been made in recent years to document the need for rapid excavation services in mining, construction, and government activities. The first effort of

this sort was made by the Committee on Rapid Excavation of the National Academy of Sciences. This committee was formed into eight panels which studied various phases of the rapid excavation process to evaluate the needs of each individual phase in the overall process. The panel reports (56)* were used to draw up the final committee report entitled "Rapid Excavation: Significance, Needs, and Opportunities" (59). This report defined the areas which were important in the rapid excavation process and outlined research activities to further technology in these area. Additional impetus was given to this effort by U. S. Bureau of Mines and U. S. Department of Transportation personnel who further justified the need for such research activity (46,28,83).

The world-wide demand for tunnelling in the future has been investigated by an international committee of engineers and scientists known as the Advisory Conference on Tunnelling of the Organization for Economic Co-operation and Development (1). This committee was concerned with polling member nations regarding the demand for tunnelling services in upcoming years and defining the areas of technology which require improvement in order to meet the challenge of providing future underground excavations at a reasonable cost. Some of the important disciplines singled out by this group included rock disintegration, rock mechanics, geologic prediction, materials handling, environmental control, and systems

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*Numbers in parentheses represent references listed in the Bibliography.

evaluation. The importance of this report can be recognized when it is realized that three papers (24,44,60) presented at the Fall 1970 Society of Mining Engineers meeting in St. Louis dealt with this report and its implications. Certainly, the demand for rapid excavation processes is well-established in the literature at this time.

Hardrock Tunnelling Practice

The success of rapid excavation processes in rock has been one of the most significant and widely publicized advances in the mining and construction industries in recent years. Nearly every mining and construction journal has published stories of successful machine tunnelling jobs, increasing the interest in this process. While the United States has perhaps been the center of tunnelling activity, machine-produced tunnels have also been produced in many other countries. The literature contains numerous articles on tunnels in the United States as well as some on foreign tunnels. Foreign examples are those driven in England (37,89) and Tasmania (5,64,69,70).

In the United States, hardrock tunnels have been driven primarily for water resource projects. Many noteworthy water tunnels have already been completed including the Oahe Tunnel in South Dakota (33,62,78), the Navajo No. 1 Tunnel in New Mexico (6,31), the Blanco and Oso Tunnels of Colorado (6,11,43), the Azotea Tunnel which crosses the Colorado-New Mexico border (6,11,45), the Starvation Tunnel in Utah (6), and the River

Mountains Tunnel of Southern Nevada (67,72,76,82). Some of these tunnels were especially successful, exceeding previous records for advancing a tunnel under equal conditions.

Other hardrock tunnels driven in the United States are also of interest here. A water tunnel was driven from Brooklyn to Staten Island (40,84) in very hard pegmatitic rocks with a somewhat unconventional machine using a pilot bit anchor. The advance of the tunnel was not impressive but indicated that machines could tunnel in very hard rock. Initial use of moles in mining operations has not been very extensive (8,38,61,73). However, successful mining applications are presently taking place at the Magma Mine in Arizona and the White Pine Mine in Michigan. An additional machine is being operated at the Climax Mine in Colorado but its advance rate has been slowed due to the very hard rock. Other tunnelling jobs in very hard rock appear to be turning out successfully. An example is the Nast tunnel in Colorado where a 10-foot diameter mole is working on a very hard granite with satisfactory advance rates where the granite is not faulted.

The materials handling systems presently used in rapid excavation of horizontal openings in hard rock do not vary significantly. The most productive tunnel systems to date have utilized modern track haulage concepts to advantage. Examples of track systems used at present have been outlined by Jacobs (30). These are generally single-track setups using California switches or "Magic Carpets" for switching trains within the tunnel. In the Oso Tunnel, for example,

California switches were located on the track at about one-mile intervals to allow trains to pass in the tunnel. The heading switch was advanced with the boring machine so that an empty train could be located beneath the gantry conveyor as soon as possible after a full train had left. The method worked rather well, permitting the tunnel to advance at an impressive rate.

Belt conveyors have not been implemented nearly as often as track haulage in hardrock tunnels. However, conveyors seem to have more promise for use in the future as they can provide a truly continuous flow of muck. A belt conveyor was chosen to back up an 18-foot mole at the White Pine Mine because the tunnel grades were considered too steep for track haulage. The belt system is performing well and may encourage others to adopt this type of conveyance system. Two other varieties of continuous haulage have not been successfully applied to date. Hydraulic conveying was scheduled for use in the Azotea Tunnel but problems forced the contractor to abandon the hydraulic system and switch to track haulage (32). Nonetheless, hydraulic conveying is planned for use in Mexico on a soft-ground project (29). Pneumatic conveying, on the other hand, seems to be far from feasible as a result of the huge volume of air required to successfully convey rock materials (16). No known projects are planned at the present time which will utilize pneumatic haulage.

Another important consideration in the selection of equipment for a tunnelling system is the type of bits to be

mounted on the mole. Bits are one of the major expenses in hardrock tunnelling and are usually of the disk type, the milled-tooth type, the kerf type, or the carbide insert type (52). Generally, the choice of bits will depend upon the rock properties expected to be encountered in the tunnel. However, very little information is evident in the literature concerning the choice of bits. This may be a natural result of the competition between manufacturers of tunnelling equipment.

Soft-Ground Tunnelling Practice

The procedure of driving soft-ground or earth tunnels by machine has become commonplace, particularly for driving water, sewer, and transportation tunnels in populated areas. Extensive work of this type has been performed in San Francisco for the Bay Area Rapid Transit System (20,71), in Chicago for the sewer system (42,65,88), in Detroit for the sewer system (39, 66), and in Southern California for water (21,51,58). Contractors presently involved in soft-ground work can often bid lower for a machine-driven tunnel than one driven by conventional methods, thus insuring the growth of earth tunnelling in the future.

The "usual" soft-ground boring device consists of a rotating cutting head or wheel fitted with cutting bits and closely followed by a full shield. The shield acts to protect the workmen and holds the back until permanent support can be erected. Due to the less demanding conditions and the large number of manufacturers in this field, the soft-ground

equipment varies more than does existing hardrock equipment. Some contractors have even produced "homemade" tunnelling devices which reportedly worked well in soft-ground situations. Machines with significantly different cutter head designs have been used with success in Texas (81) and California (80). Another mole-type device used in driving the Saugus tunnel in Southern California has applied a completely unique approach to advancing the face (51). This machine contains a boom-mounted digger not unlike that of a backhoe. The digger claws into the face, filling itself with muck to be deposited on a conveyor. As the tunnel is advanced, the shield is also advanced in the usual manner.

While many different types of moles have been used in soft-ground work, the materials handling methods have not been as variable. Track systems again predominate with only token competition from other materials handling methods. Under long haul conditions a track system would not normally be able to handle the muck production of these machines. However, most earth tunnels are driven at depths which permit the placing of shafts at relatively close intervals along the tunnel route. Thus, the haul distance is considerably shorter than it would be in a typical hardrock tunnel. Nonetheless, the moles used in soft ground often out-produce the materials handling equipment by a considerable amount, resulting in a materials handling bottleneck (25). To improve the materials handling capability, some attempts have been made to implement continuous haulage methods. For example, a belt conveyor

system has been successfully used in a sewer project in Detroit (66). In a similar experiment, a hydraulic transport method has been attempted in Mexico (29) although no publications are presently available on the results.

Cutting edges or bits for earth tunnelling equipment are generally of the carbide-tipped type or of the tooth-type similar to those used on power shovel buckets. Because of the less severe conditions, advante occurs at a more rapid pace than in hard rock. However, soft-ground systems are often slowed considerably when boulders or other hard materials are encountered. Adequate knowledge of the geologic conditions to be met is thus required to insure that the tunnel can be driven with a soft-ground machine.

One procedure which has become standard in both hard and soft ground is the use of a laser-beam guidance system (22, 35,36). The laser is generally mounted on a transit base which is clamped to the side of the tunnel. When the beam is properly oriented, the machine operator can determine if the tunnel is being driven according to the correct grade and direction by observing the laser beam location on two targets attached to the mole. This method has been so successful that it will probably remain the standard for many years.

Rock Mechanics Applications

The application of rock mechanics principles to problems related to the driving of tunnels in soil or rock has not been extensively investigated to date. General information on the type of bits to use in rock of various strengths, the amount

of force required on the cutting head, and the cutting head speed has been discussed (9,15). However, more extensive research into the area of bit design and cutter effectiveness is probably warranted. One study of this type (47) has investigated the cutting effectiveness of disk cutters in sedimentary and metamorphic rocks. More extensive studies of this type would probably provide better information to enable operators to choose the best cutter type and design for the various types of rock to be encountered in a tunnel.

Another area which appears to require additional research is the design of tunnel support and liners. It has been said (2) that the present design for tunnels are based upon the assumption of the most unfavorable possible conditions. This is a method of attack which will, of course, result in extremely high cost. However, since present tunnels are seldom instrumented to determine the magnitude of the job required of the support system, no other method is possible. Better methods of determining the stresses to be assumed by the tunnel support or liners must be found to bring liner costs into a more reasonable range.

Progress has been made in research involved with the application of new and unique rock breakage techniques to rapid excavation processes. Cutting with hydraulic jets appears to offer the most promise at the present time. Experiments with hydraulic jets are producing results which may make hydraulic cutting feasible within a few years (54). One manufacturer of tunnelling devices, Calweld, is supposedly working on a

machine using this principle which may be marketed within two years.

Systems Analysis of Tunnelling Operations

The systems approach has been suggested as a logical method of studying the overall tunnelling system. The first publication found which outlined such an approach was authored in 1967 by Howard (27). Further attention was paid to the need for systems evaluation in the Organization for Economic Co-operation and Development report on tunnelling (1) where numerous requirements of the tunnelling industry were surveyed. The first detailed papers concerned with the systems approach were presented at the Second Symposium on Research and Development in Rapid Excavation at Sacramento State College in 1967. At this meeting, Bledsoe presented his ideas on the application of systems analysis to tunnelling (10). The primary purpose of such a study of the overall tunnelling process is to attempt to eliminate the mismatch in capacity between tunnelling subsystems which has occurred in the past. A similar avenue of study applied to the problems of soft-ground tunnelling was presented by Willis and Stone (87). While these publications presented the basic principles to be used, no detailed work was available until a later date.

A study of the materials handling systems for tunnelling was completed recently by Holmes and Narver, Inc., for the U. S. Department of Transportation (16). This study was very comprehensive and considered all the presently known

methods for handling muck for tunnelling operations of various types. Detailed cost and feasibility studies were summarized and discussed in the report. However, while the systems study made use of the availability of each subsystem, the possible interference of individual subsystems with each other in the tunnel was not investigated or considered. This is revealed in the assumption that "all systems (excavation, support installation, material handling, and project support) operate continuously without interruption throughout the entire 24-hour period" (16, p. 15-1). In reality, the subsystems cannot operate uninterrupted. It is a fact that the tunnelling machine must often wait on other subsystems. Thus, this study ignored this important systems aspect of the problem.

THE CONCEPTUAL MODEL

A conceptual model of any system consists of the collection of concepts and principles necessary to construct the model. The model of a tunnelling system which has been proposed is to be constructed in a computer language. The concepts used in constructing such a model will be outlined here. The diagram in Figure 1 shows the relationship between the various components of the model. The simulation control system is the main program and the heart of the model, coordinating the submodels and linking them to the input and output data. The submodels of the unit operations shown in the diagram will be in the form of subroutines and will generate the data on the performance of the unit operations in the tunnel. Both the control system and the unit operation submodels will be discussed further in the following paragraphs.

Simulation Control System

The control system of the simulation model will be the center for controlling the various submodels that make up the overall computer model. It serves several very important functions including input-output, control of the interaction and interrelationship between the various unit operations, and data accounting.

The most important task of the simulation control system is to accurately model the interaction of the various subsystems of the tunneling operation. The design of such a program will be aimed toward handling any conceivable set of

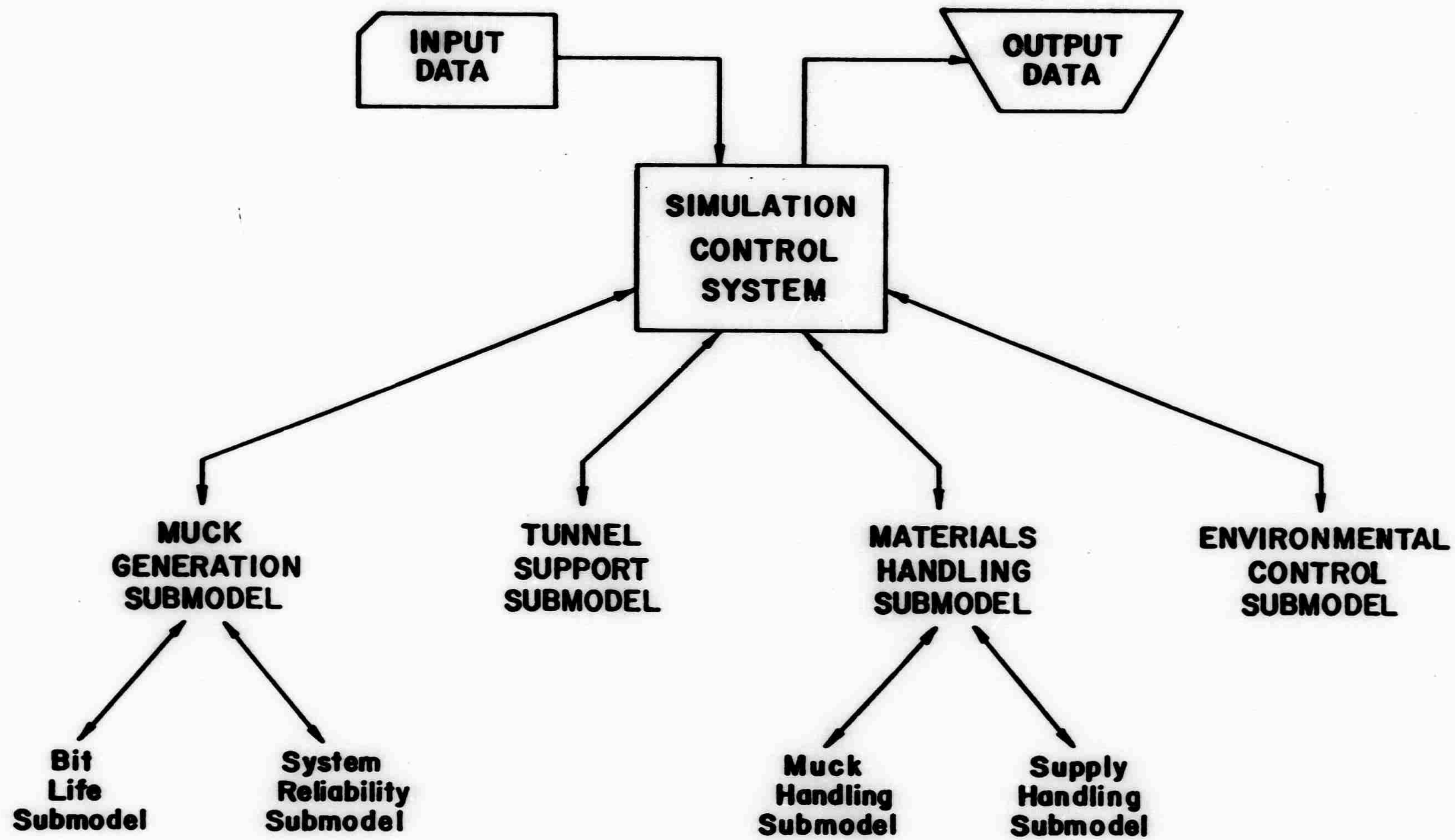

Figure I - RELATIONSHIP OF THE COMPONENTS OF THE COMPUTER MODEL

priorities which can exist between the unit operations. For example, the tunnel support subsystem may have the controlling or top priority in tunnel operations where support is required for immediate safety. However, where the roof control work is being performed for purposes of long-term support only, the roof control procedures may not have priority over the other processes during the advance of the tunnel. Similar variations apply in the environmental control process. The processes to be simulated in the environmental control model may have priority over muck generation in some tunnels but much less priority in others. Thus, the simulation control system will regulate all the subsystem priorities to be used in simulation.

The input and output functions are also logically handled in the control system of the program. The data will be read into the main program and transferred to the unit operation submodels, which will be programmed as subroutines, as needed. Upon receipt of the data, the subroutines will generate time and activity data and return it to the control system for accounting purposes.

The accounting process handled by the simulation control system will keep a record of all the important variables in the model and will be a relatively straightforward application of the digital computer. However, attention must be paid to the process of obtaining and keeping track of the data in the most expedient and economic manner. Emphasis will be placed upon developing the simulation model and the accounting system

in an event-oriented manner rather than in a time-oriented manner. This will facilitate the accounting operation and the data output. The output will be of two types, an optional continuous log of operations and a summary package for evaluation purposes.

<u>Muck Generation Submodel</u>

The generation of muck at the face of a tunnel is the process which controls the tunnel advance. The process of muck generation is controlled by many variables including the rock properties, the reliability of the equipment, the disposition of the bits, and the availability of back-up equipment. These variables must be considered to accurately model the muck generation process. The reliability of the tunnel equipment is one variable which must be handled by investigating the historical record of the equipment. The data will then be used to produce the operational and non-operational time distributions of the equipment.

The process of changing bits on the machine is normally one which will result in a considerable amount of machine downtime. For this reason, the changing of bits must be considered as part of the muck generation model. One of the simplest methods of including the bit changes would be to include them in the non-operational time distribution of the mole. However, since bit changes can often be done at shift-change time, such a procedure would result in inaccuracies. Therefore, the simulation of bit changes will be performed

by a separate bit life submodel which will feed information back to the muck generation subsystem.

The bit life model must be general enough to accommodate the numerous types of bit replacement situations which may be encountered. To accomplish this, a general model will be used as indicated in Figure 2. Here, a simplified tunnelling machine will be used to illustrate the concept. Bits are placed on a tunnelling machine in a prearranged design (the machine cutting head illustrated in Figure 2 has 11 such bits.) For most tunnelling machines, the bits do not exhibit equal wearout characteristics because the circumferential distance of travel and other variables are not uniform. A separate bit life distribution will therefore be required for each position on the face of the machine. By numbering each position and generating each bit life from a separate distribution, any conceivable situation can be modelled realistically. The case of a machine on which all bits are changed at a single time can be simulated by assigning a single probability distribution to the entire change rather than individual probability distributions to each bit.

The availability of the back-up systems is one variable which will not be handled by the muck generation subsystem itself. Instead, the bit life and machine reliability results will be fed back to the simulation control system which will then evaluate the status of the remaining subsystems and handle the interactions which occur between the muck generation subsystem and the remaining sybsystems.

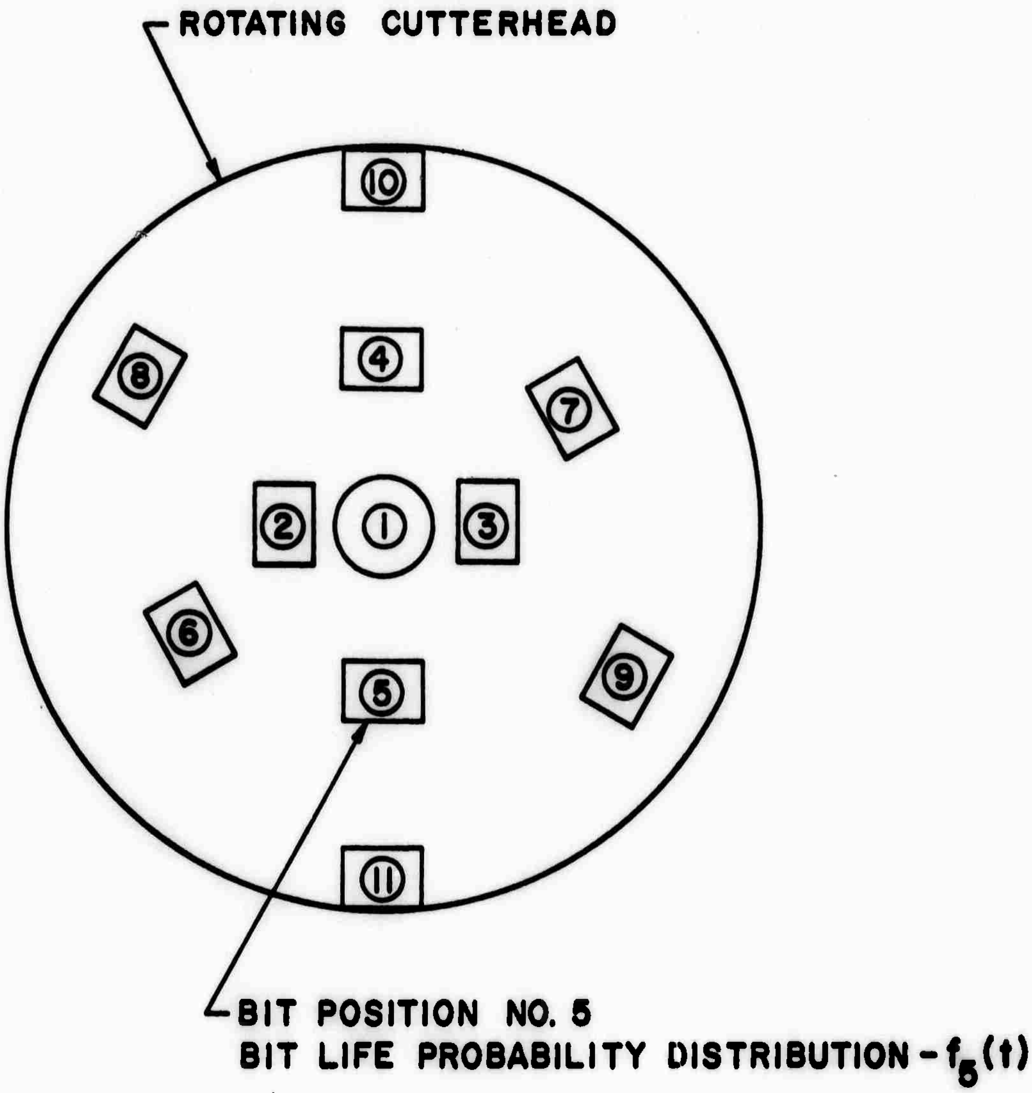

Figure 2 - SCHEMATIC OF A REPRESENTATIVE CUTTERHEAD SHOWING THE METHOD OF NUMBERING BIT POSITIONS

The rock properties in the tunnel will affect the advance and muck generation rate in any machine tunnelling operation. Thus, the rock properties must be considered if the advance rate of the machine is to be determined. For this project, it will be assumed that the advance rates can be predicted if the properties of the rock are known. This data can then be used in the computer model to generate the instantaneous rates of advance from a probability distribution.

Tunnel Support Subsystem

The support or roof control function is quite variable in excavation work because of the extreme variation in materials through which excavations are driven. Most tunnels are provided with support in a cyclic fashion, i.e., a cycle of jobs is carried out to advance the support system by one "set." There is also some use made of methods such as guniting which are not cyclic in nature. These methods can be somewhat more continuous in furnishing support for the excavation. The amount of work required will depend upon the degree of support required to provide a stable opening.

Simulation of a cyclic method will be performed using a probability distribution for the time required for one cycle of support advance. This is a logical procedure since the muck generation subsystem cannot advance until the cycle is completed. Modelling of a continuous method will be handled by generating a continuous advance rate which will apply for a predetermined period of time. Each time period will have a different advance rate and the tunnelling machine will be allowed to advance

along with the support.

The speed and pattern of providing the tunnel with support will determine whether the muck generation subsystem can advance uninterrupted or whether it must periodically wait for the tunnel support to catch up. This will not be determined in the support subsystem, however, as the simulation control system will work with the interactions between these unit operations.

Environmental Control Submodel

Maintaining the tunnel environment is a process which normally consists of maintaining adequate ventilation at the face and the water supply at the machine if it is used for dust control. Several other operations may also be involved in a particular tunnel. The process of providing these auxiliary needs will normally be performed at specific intervals of tunnel advance. The execution of these periodic advances of the environmental services is a relatively simple one under ideal conditions and will not normally delay the overall operation significantly. However, environmental control can be complicated by the materials handling system which delivers the supplies. The ventilation system, in particular, will require supplies of a size which may not permit storage close to the face. As a result, the deliverance of these supplies may be just as important in the environmental control function as the installation of the supplies.

The advancing of the ventilation and other utilities can be modelled stochastically in the computer program. The

interrelationship between this function and the other subsystems will be accounted for in the logic programmed into the control system.

Materials Handling Submodel

The materials handling operation is perhaps the most complex to model. This is a result of the fact that the materials handling subsystem can vary considerably and may require two distinct types of handling mechanisms, one for the muck and one for the supplies. For purposes of simulation, the materials handling systems can be classified as continuous or cyclic.

Continuous materials handling systems are those which can convey muck from the face of the tunnel in an uninterrupted fashion. The types of materials handling subsystems which are continuous and presently feasible include belt conveyors, and hydraulic or pneumatic conveyance systems. The simulation of the material movement in such devices is easy to simulate using a deterministic model. The loading and dumping at each end, however, may be probabilistic due to the inherent nature of the process or due to the interaction of the materials handling subsystem with the rest of the overall system. Nonetheless, the continuous systems offer less challenge than do the cyclic methods.

Materials handling using cyclic transportation systems such as track or rubber-tired haulage is a simulation problem which can be handled using either a stochastic or deterministic approach. This may be illustrated by considering the haulage

layout shown in Figure 3. The schematic can conceivably represent either a track haulage setup using California switches or a "truck" transportation system in which the trucks are limited to passing only at designated locations in the tunnel where switchouts have been excavated. On a track setup of this type, a train operator moves from switch to switch by observing the block signals. If no train is using the next section of track, he continues his haul until the signals indicate an approaching train. Then, he waits in the proper siding until the approaching train has passed. To simulate this situation stochastically, the travel time distributions for each track section between switches must be determined. In Figure 3, these are designated as $f_{A-B}(t)$ and $f_{B-C}(t)$. These distributions are easily obtained for a particular system through time studies but are not predictable for a hypothetical system due to the large number of determining variables. Thus, while the mathematical procedure is reliable the data may not be predictable for all situations to be simulated.

An alternate method for simulating a cyclic transportation method is to use a deterministic approach in determining the switch-to-switch travel times. To perform this type of analysis, it is necessary to utilize the physical laws of motion and the characteristic curves of the equipment to simulate the haulage activities. This is accomplished on a digital computer by applying the principles of motion repeatedly for short time intervals until the haulage run desired is complete. The obvious advantage of this approach is the possibility of

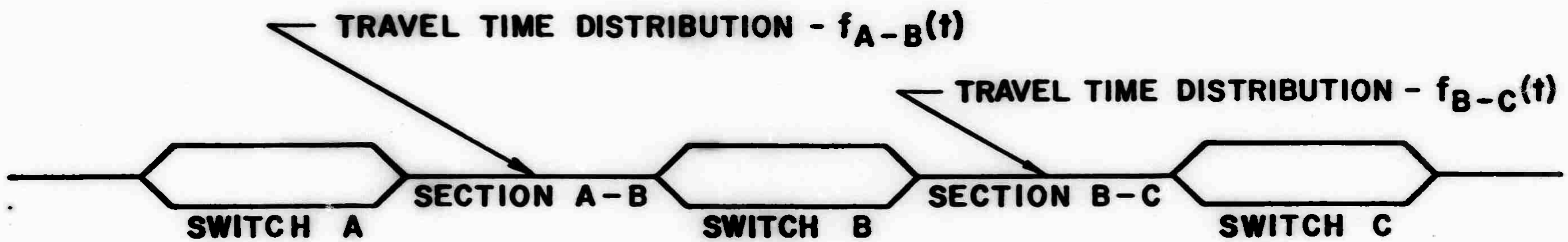

Figure 3 - SCHEMATIC OF A HAULAGE SYSTEM WITH THREE SWITCHES

generating travel times for any possible length and grade of haul and any payload. Based on this fact, the deterministic method will be used to simulate the travel times for cyclic transportation methods. As a result, stochastic variations in the travel time will result only from random variations in the payload. Data generated in the materials handling subsystem will be returned to the simulation control system for processing with the data returned from the other subsystem subroutines.

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